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ANALYTICAL INVESTIGATION OF THE EFFECT OF TURBOPUMP DESIGN ON GROSS-WEIGHT CHARACTERISTICS OF A HYDROGEN-PROPELLED NUCLEAR ROCKET

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SUMMARY

The effect of turbopump design on rocket gross weight was investigated for a high-pressure bleed-type hydrogen-reactor long-range rocket with a fixed mission. Axial-flow, mixed-flow, and centrifugal pumps driven by single and twin turbines were considered.

With an efficiency of 0.7 assumed for all pumps, the lowest rocket gross weights were obtained with an axial-flow or a mixed-flow pump driven by a single turbine of at least eight stages. All turbopump combinations could be used, however, with gross weight varying less than 8 percent for a given payload.

Turbopump efficiencies have a significant effect on the ratio of gross weight to payload with the magnitude of the effect determined by the ratio of rocket structural weight to total propellant weight. One point in pump efficiency is worth 0.2 percent in gross weight for a given payload with a structural weight parameter of 0.1, and 0.6 percent with a structural weight parameter of 0.2.

Turbine and pump weights are much less significant in terms of gross-to-pay weight ratio than the efficiencies of these components. One point in pump efficiency is equivalent to approximately 13 percent in pump weight, while 1 point in turbine efficiency is equivalent to about 7 percent in turbine weight.

INTRODUCTION

The characteristics of a rocket with given payload, mission, and thrust-chamber conditions are affected in two ways by the turbopump: (1) The mass of the turbopump must be accelerated to the burnout velocity and consequently influences the expenditure of propellant; and (2) the turbine flow rate, that fraction of the propellant flow that is diverted through the turbine, directly influences the effective specific impulse of the propellant. These considerations indicate the desirability of low turbopump weight and low turbine flow rate.

The effect of turbopump design, and hence of turbopump weight and turbine flow rate, was investigated for a high-pressure bleed-type hydrogen-propelled rocket with a nuclear-reactor heat source. This was done for a vertical flight that was determined as the equivalent of an earth-satellite mission. Turbopump weights were calculated for three types of pumps: axial flow, mixed flow, and centrifugal, driven by single turbines and by two turbines in flow parallel. Investigation of these systems required consideration of the number of turbine stages and turbine flow rate as independent variables.

This report presents the pump and turbine design information, the method used in matching the turbopump components for the prescribed vertical flight, and results of the investigation in terms of the ratio of gross weight to payload for each turbopump type, the number of turbine stages, and two rocket structural-weight parameters.

DESCRIPTION OF ROCKET SYSTEM

Rocket Requirements and Characteristics

A single-stage, hydrogen-propelled nuclear satellite vehicle was selected for investigation. A propellant bleed system was considered for supplying the power required to pump the liquid hydrogen from the tank storage pressure to the reactor inlet pressure. This system diverts a small fraction of the pump exit flow to a suitable heat source for heating to the turbine temperature, after which it expands through the turbine to provide the required pump shaft power. A diagram of the components of the system and flow between the components is shown in figure 1.

It was assumed that the turbine exhaust gas would result in no thrust in the direction of flight. The effect of turbine flow on effective specific impulse of the total propellant flow may therefore be shown as follows:

$$I_{eff} = I(1 - y) \tag{1}$$

where I is the rocket-nozzle specific impulse and y is the bleed rate, the ratio of turbine flow to pump flow. (All symbols are defined in appendix A.) The rocket-nozzle specific impulse used in this equation was 740 seconds and corresponds to a reactor temperature of 4500° R and a nozzle area ratio of 25. Effective specific-impulse values for a range of bleed rate were calculated and used in the equations for velocity and altitude at burnout for vertical flight with no atmospheric drag and constant gravity. The equation for velocity,

$$V_b = I_{eff}\, g \ln\left(\frac{W_g}{W_e}\right) - gt_b \tag{2}$$

is equation 12-18 from reference 1, with the mass conversion and gravity terms assumed equal and constant. The equation for altitude,

$$h_b = t_b\left(I_{eff}\, g - \frac{V_b + gt_b}{\frac{W_g}{W_e} - 1} - \frac{1}{2}\, gt_b\right) \tag{3}$$

is a rearranged form of equation 12-20 of reference 1. Since each value of bleed rate results in a value of effective specific impulse, equations (2) and (3) may be solved simultaneously when V_b and h_b are specified. The vertical mission was used to simplify the determination of turbopump and bleed-rate effects and was determined as the equivalent of the satellite launch mission. It was equivalent in that the effective specific impulse, the ratio of gross weight to empty weight, and duration of powered flight were the same. Numerical values used to determine the reference vertical mission were as follows:

Effective specific impulse, I_{eff}, sec	718
Bleed rate, y	0.03
Ratio of gross weight to empty weight, W_g/W_e	4.93
Duration of powered flight, t_b, sec	337

The vertical mission corresponding to these values included a velocity at the end of powered flight of 26,000 feet per second and an altitude of 2,800,000 feet. This burnout condition was held constant for all subsequent calculations.

Figures 2 and 3 show gross-to-empty weight ratio W_g/W_e and time t_b as functions of bleed rate y for this equivalent vertical mission.

A reference payload of 10,000 pounds was used where necessary in estimating component weights. The component weights were assumed linear with pump flow rate. Although this is not strictly correct for wide ranges in pump flow rate, the comparisons among the various turbopump systems investigated are valid because flow rate varies only slightly from one turbopump system to the next for any given payload.

Relation Between Rocket and Turbopump

Turbopump weight is related to payload, propellant, and structural weights as shown in the following equation:

$$W_g = W_e + W_{pr} = W_L + W_{TP} + W_{pr} + \bar{S}W_{pr} \tag{4}$$

where the last term represents the structural weight and includes the reactor, nozzle, guidance, connective structure, and so forth. The term $\bar{S}$ is defined as the ratio of this structural weight to total propellant weight. Equation (4) can be rearranged to provide an expression for the ratio of gross weight to payload:

$$\frac{W_g}{W_L} = \frac{\frac{W_g}{W_e}}{1 - (\bar{S} + \Delta S_{TP})\left(\frac{W_g}{W_e} - 1\right)} \tag{5}$$

where ΔS_{TP} is equal to W_{TP}/W_{pr}.

The ratio of gross weight to empty weight for a given vertical mission is a function of bleed rate, as shown in equations (1), (2), and (3); so the ratio of gross weight to payload may be shown as a function of ΔS_{TP} for a given value of the structural parameter $\bar{S}$ and the bleed rate y. Two values of $\bar{S}$, 0.1 and 0.2, were used in the subject investigation and are representative of the range of values currently being considered for this type of rocket. Results of calculations made with ranges of bleed rate and turbopump weight parameter are shown in figure 4 for both values of the structural parameter (this figure is discussed later in the report).

Pump Requirements

A tank storage pressure of 50 pounds per square inch absolute was arbitrarily specified with a reactor operating pressure of 1200 pounds per square inch absolute, thus specifying operating pressures for the pumps to be considered. Pump speed was determined from considerations of turbopump weight and pump cavitation. A high rotative speed is desirable to keep the turbomachinery dimensions and weight low, but cavitation at the pump inlet limits the speed to values at which cavitation will not seriously impair pump performance. A fairly conservative value of suction specific speed SS (commonly used to indicate the severity of cavitation) of 20,000 was selected as a design limit for the inducer or inlet stage.

DETAILS OF TURBOPUMP CONSIDERATIONS

Turbopump Configurations Considered

Three pump types were considered for the subject application: axial flow, mixed flow, and centrifugal. These pumps were to be driven directly by one or two turbines. One and two turbine drive systems were considered in order to determine which was most advantageous for each pump type. Turbine exit flow area is limited by blade and disk stresses at any given rotative speed, so that turbine pressure ratio, and consequently specific work, is limited. The use of twin turbines, each of which utilizes half of the bleed flow at the same rotative speed and exit flow area, provides twice as much exit flow area per pound of turbine flow and thus the possibility of more work per pound. The increased potential in turbine specific work will result in lower required bleed rates for a given shaft work. The two-turbine system is heavier, however, and the net effect of decreasing the bleed rate while increasing the turbine weight must be determined.

Seven combinations of pumps and turbines were considered in the subject investigation and are shown schematically in figure 5. They may be described briefly as follows:

(1) Axial-flow pump with single turbine. This system has turbine and pump thrusts acting in opposite directions. These thrusts were approximately equal for the matched turbine and pump with the 10,000-pound-payload case, and a thrust bearing was considered adequate to support the thrust load.

(2) Mixed-flow pump with single turbine. This pump includes two loaded stages in addition to the inducer stage, each of which had a thrust approximately equal to the turbine thrust for the reference 10,000-pound-payload case. The two pump stages were arranged for opposing thrust, and a balance device was required to compensate for the turbine thrust. The pressures causing the turbine thrust, upstream of the first rotor and downstream of the last rotor, were therefore used to load the rotating balance disk, which was slightly smaller than the rotor hubs. The chambers on opposite sides of the balance disk were separated by a peripheral seal on the disk. Weight of the seal assembly was calculated for the reference case and was divided by the reference pump flow to obtain a balance-assembly weight parameter W_B/w_P to include in the turbopump weight parameter.

(3) Centrifugal pump and single turbine. The arrangement of parts and the method for determining balance-assembly requirements were the same as for the previous combination.

(4) Axial-flow pump and twin turbines. Because the thrusts of the pump and one turbine were approximately equal, a balance assembly was required to balance the thrust of the other turbine.

(5) Divided axial-flow pump and twin-turbine drive. This system employs the same axial pump divided, so that the two groups of stages will have equal thrusts that can be opposed to result in no net thrust.

This eliminates the need for a balance assembly, since the turbine thrusts can also be opposed.

(6) Mixed-flow pump and twin-turbine drive. This system can be designed for little or no shaft thrust, so that no balance disk was necessary.

(7) Centrifugal pump and twin-turbine drive. This system is essentially the same as the mixed-flow-pump - twin-turbine system regarding arrangement of parts and shaft thrust considerations.

Pump Designs

Three pumps, axial-flow, mixed-flow, and centrifugal, were designed in sufficient detail to give reasonably accurate weight determinations. The pump designs are shown in figure 6, and the design parameters are given in table I. Each pump included an inducer stage to add enough head so that the following pump stages would not cavitate. Some of the features of the individual types of pumps are discussed in the following paragraphs.

<u>Axial-flow pump</u>. - The axial-flow pump was designed for a rotative speed of 20,000 rpm, which corresponds to a suction specific speed of 19,400 for the design reference flow rate of 360 pounds per second and a suction head of 1150 feet. This flow rate corresponds to the reference payload of 10,000 pounds, a structural weight parameter of 0.165, and a turbopump weight parameter of 0.007. The inducer inlet was optimized by the method shown in reference 2 for a 0.5 hub-tip radius ratio. The loaded stages have the same tip radius as the inducer, but the hub-tip radius ratio was increased from 0.5 to 0.6 to get acceptable blade stresses in the loaded stages by decreasing the bending moment. Bending stresses were larger than centrifugal stresses, so a reduction in bending moment effectively reduced the total stresses.

In addition to the inducer, eight axial stages with constant energy addition were selected. Twenty-five blades per stage were used so that a high blade solidity could be maintained with a small blade chord. These design conditions were selected to obtain acceptable pump performance according to the concepts advanced in reference 3.

<u>Mixed-flow pump</u>. - The mixed-flow pump was also designed for a rotative speed of 20,000 rpm. Two mixed-flow pump stages were required to develop the design head, because the stresses in a single stage were too great at the required single-stage rotor tip speed with either high-strength stainless steel or aluminum. By developing equal head in two stages, the rotor tip speed was reduced sufficiently so that either a stainless steel or an aluminum rotor could be used. The stainless steel

and aluminum rotors have about the same limiting tip speed in this case because (1) the blade bending stress is much less than rotor centrifugal stress, and the blade bending stress is not maximum where the centrifugal stress is maximum; and (2) the limiting-stress-to-density ratios are about the same for both materials. The aluminum rotor was selected because it is lighter.

A pump inlet radius lower than the optimum inducer tip radius (from cavitation considerations) is desirable in order to obtain a larger blade over which the loading can be distributed. The blade hydrodynamic loading was considered to have a greater effect on the over-all pump efficiency than that of optimizing the inducer inlet for cavitation. An inducer with a tip radius of 89 percent of the theoretical optimum tip radius was selected. The pump inlet tip radius was 82 percent of the theoretical optimum inducer tip radius. It was assumed that the reduction of inducer pump dimensions would not decrease the pump reliability with regard to cavitation, especially at a suction specific speed of only 19,400. It was also assumed that any changes obtained in over-all efficiency by the reduction in size from the theoretical optimum are more than offset by the weight savings over a mixed-flow turbopump unit that uses the optimum pump inlet by turning at a lower rotative speed.

Centrifugal pumps. - Based on a consideration of centrifugal and blade bending stresses, a tip-speed limit for the centrifugal pump was set at 1200 feet per second for this application. Because the required head cannot quite be developed in one stage, the centrifugal pump is penalized in this comparison of pump types by having to use two stages that cannot utilize to full advantage the high tip speed available from stress considerations.

An outlet-to-inlet radius ratio of 1.8 was selected as a lower limit for radial blades from the standpoint of the blade loading. The combination of a required tip speed of 980 feet per second, a minimum radius ratio of 1.8, and a desired rotative speed of 20,000 rpm with the weight flow of 360 pounds per second resulted in a high inlet axial velocity and an inlet radius much less than the theoretical optimum inducer radius, so the rotative speed was reduced to 16,000 rpm, which resulted in a larger tip diameter for this pump than for either of the other types.

Split axial pump. - The split axial pump is the same hydrodynamic design as the axial pump with a different mechanical arrangement to reduce the pump thrust and, hence, to eliminate a balance assembly for the twin-turbine arrangement.

Pump Weight Estimates

The weight of each pump was estimated from design layouts for the reference payload of 10,000 pounds and its associated pump flow rate of 360 pounds per second. It was assumed in the investigation that pump weight is linear with pump flow rate, so that each pump was associated with a constant value of the ratio of pump weight to pump flow rate W_P/w_P. A balance-assembly weight parameter W_B/w_P was also estimated for each turbopump type and was held constant. Table I shows values for these parameters. The assumption of constant weight parameters is considered sufficiently accurate for comparisons among pump types for any given application. A pump efficiency of 0.7 was assumed for the designs used in estimating weights. Differences in efficiency would affect these dimensions slightly by changing fluid densities within the pump and in the exit diffusers. This effect was neglected in evaluating the effect of pump efficiency on the rocket.

An additional parameter, $w_P N^2$, is a constant for each pump type and is useful in pump-turbine matching as shown subsequently. This parameter is shown to be a constant from the continuity equation at the pump inlet and the relation between tip speed and rotative speed:

$$w_P = \rho V_x \pi r_t^2 \left[1 - \left(\frac{r_h}{r_t}\right)^2\right]$$

$$N = \frac{60\ U_t}{2\pi r_t}$$

The parameter $w_P N^2$ can then be written

$$w_P N^2 = \frac{900}{\pi}\ \rho V_x U_t^2 \left[1 - \left(\frac{r_h}{r_t}\right)^2\right]$$

The terms appearing to the right are independent of size and flow rate, and thus the parameter $w_P N^2$ is constant for each pump type.

Turbine Considerations

Reference 4 describes a method for relating turbine weight to pump flow, pump work, blade speed, inlet gas conditions, bleed rate, and number of turbine stages. Included in this reference is a set of curves relating turbine efficiency to the speed-work parameter λ and to the number of turbine stages. Loss coefficients used in the determination of this relation were obtained from cold-air tests of small transonic turbines. These curves were used in the subject investigation with the assumption that the trends in efficiency with the speed-work parameter and turbine staging would be the same with pure hot hydrogen. The levels of efficiency may be somewhat different for hydrogen, but this would not significantly affect the results of conclusions obtained in the investigation because all combinations of turbines and pumps would be affected in the same manner.

The pump work was calculated as that required to pump the liquid hydrogen from a tank storage pressure of 50 pounds per square inch absolute to a pump exit pressure of 1200 pounds per square inch absolute with a pump efficiency of 0.7. This resulted in a pump specific work of 68.8 Btu per pound. Turbine specific work is therefore 68.8 divided by the bleed rate. All turbine designs considered included a blade tip speed of 1400 feet per second and an exit hub-tip radius ratio of 0.79. These numbers correspond to limiting blade and disk centrifugal stresses with high-temperature alloys now in use. A constant-stress disk design was selected in order to permit the use of high blade speeds. Some of the details of this disk design are shown in figure 7, which is representative of the turbines considered in the subject investigation. This figure shows a multistage turbine designed for limiting disk and blade stress and for work requirements corresponding to the pump considered herein. The design turbine inlet temperature was 1860° R in each case. With an assumed pressure drop of 200 pounds per square inch through the reactor heat exchanger and throttle valve, the turbine inlet pressure was 1000 pounds per square inch absolute.

The calculation method of reference 4 was used to relate the ratio of turbine weight to pump flow to the ratio of turbine frontal area to pump flow for several values of bleed rate. This is shown in figure 8, which was used in matching turbines and pumps as described in a subsequent section of the report. Turbine weights were determined with the following equation, which shows turbine weight as a function of turbine frontal area A_T and stage number n.

$$W = 70A\sqrt{n} \tag{8}$$

This equation represents within 10 percent the weights of a series of rocket turbines previously designed and is discussed in reference 4.

Matching of Turbopump Components to Determine

Rocket Gross Weight Variation

Turbine frontal area $\pi r_{t,T}^2$ may be expressed as a function of turbine tip speed and rotative speed:

$$A = \frac{900}{\pi} \frac{U_{t,T}^2}{N^2} \tag{9}$$

Dividing each side by the pump flow results in an expression for the ratio of turbine frontal area to pump flow rate, one of the parameters plotted in figure 8:

$$\frac{A_T}{w_P} = \frac{900}{\pi} \frac{U_{t,T}^2}{w_P N^2} \tag{10}$$

Turbine tip speed is constant at 1400 feet per second, as noted previously, and each pump type is associated with a single value of the quantity $w_P N^2$, and consequently of the turbine area parameter. This area-parameter value is applicable for either a single-turbine or a twin-turbine drive, and w_P in both cases refers to the entire pump flow.

Single-turbine matching. - The method used in matching the turbopump components and the rocket for each turbopump configuration at several bleed rates may be summarized as follows for a single-turbine drive:

(1) Several bleed rates are selected.

(2) The turbine weight parameter W_T/w_P is read on figure 8(a) for each bleed rate at the turbine area parameter appropriate to the pump type being investigated.

(3) The turbine weight parameter for each bleed rate is then added to the pump weight parameter W_P/w_P and the balance-assembly parameter W_B/w_P to obtain the total turbopump weight parameter W_{TP}/w_P.

(4) The duration of powered flight t_b is read from figure 3 for each bleed rate.

(5) The turbopump weight parameter is then divided by burning time to obtain $W_{TP}/w_P t_b$ or ΔS_{TP}, the abscissa of figure 4.

(6) The ratio of gross weight to payload is then read from figure 4 for each bleed rate and its associated value of ΔS_{TP} from step 5.

(7) The number of turbine stages is determined with equation (8) and the turbine area and weight parameters of step 2. This is necessary because the values of W_T/w_P obtained in step 2 correspond to fractional numbers of turbine stages.

(8) The ratio of gross weight to payload is then plotted against the number of turbine stages to obtain solutions for gross-to-pay weight ratio at integral numbers of turbine stages.

An example of this procedure is shown in Appendix B.

Twin-turbine matching. - Matching the various pumps with the twin-turbine drives required that one-half the total bleed rate be used in step 2 with figure 8(b). The curves for figure 8(b) were determined for one-half the total pump work and a low rate of bleed. It is also required that the turbopump weight parameter in step 3 include the weight of both turbines, twice the value of W_T/w_P read in step 2 from figure 8(b). All other steps in this procedure are identical with those of the single-turbine procedure.

RESULTS

Effects of Turbopump Design on Gross-to-Pay Weight Ratios

Figures 2 and 3 show the effect of turbine flow rate on the ratio of gross weight to empty weight and on burning time for the vertical flight used in the analysis. Both of these quantities increase steadily with increasing bleed rate because of the correspondingly decreasing effective specific impulse. The values shown in figures 2 and 3 are independent of the rocket structure, and consequently of turbopump weight, and were used to relate the structure, payload, and turbopump to gross weight through the effect of bleed rate.

Figure 9 shows the ratio of rocket gross weight to payload for each turbopump type investigated over a range of the number of turbine stages, for two rocket structural weight parameters, 0.1 and 0.2. All curves show rapid increases in gross weight as the number of turbine stages is decreased below eight; this indicates that large numbers of turbine stages are desirable for any turbopump combination. These increases in gross weight result from the higher turbine flow rates required to produce the shaft power at the lower numbers of stages and the associated lower turbine efficiencies. A second point of interest is that, for each pump type, the twin-turbine drive resulted in a higher ratio of gross weight to payload than the single-turbine drive. The reduction in bleed rate made possible by doubling the turbine exit flow area was accompanied by a doubling of turbine weight at any given number of stages in each turbine. The turbine weight increase predominated, however, resulting in greater rocket gross weight as well as greater cost and complexity. It is apparent, then, that the twin-turbine drive is undesirable for this rocket regardless of pump type. Parts (a) and (b) of figure 9 indicate these trends in the same manner but at different levels of gross-to-pay weight ratio as dictated by the two selected structural parameters.

Turbines with twelve stages were arbitrarily selected to compare the various turbopump systems, since the gross-to-pay weight ratio for each system reaches a value at or near its minimum value at this number of turbine stages. Table II shows the gross-to-pay weight ratio for both structural weight parameters for twelve-stage turbines. The differences among the turbopump types at the lower structural weight parameter are rather small, with all types resulting in gross-to-pay weight ratios between 8.19 and 8.43, a spread of only 2.9 percent. The single-turbine drive systems gave gross-to-pay weight ratios varying between 8.193 and 8.273. This is a range of only 1.0 percent and is equivalent to 800 pounds of gross weight with a payload of 10,000 pounds. The twin-turbine drive systems result in higher gross-to-pay ratios as noted previously, and with each drive system the highest gross weight is associated with the centrifugal pump. This occurs because of the lower rotative speed that resulted from pump design considerations. This lower rotative speed in combination with the fixed-turbine-blade tip speed resulted in a large turbine diameter with the centrifugal pump, and consequently a heavier turbine. It may be noted again at this point that the conditions selected for the subject investigation impose a penalty on the centrifugal pump system. A lower head rise or higher permissible tip speed, for example, would permit the use of a single centrifugal pump stage and a higher rotative speed. This in turn would result in a lighter turbine and rocket gross weights very near those associated with the axial- and mixed-flow pumps.

Ratios of gross weight to payload corresponding to a rocket structural weight parameter of 0.2 lie between 23.51 and 25.43, a spread of about 7.8 percent. The turbopump systems compare in exactly the same manner as with the lower structural parameter, since the structural weight parameter as used in this report has no effect on the turbopump system. The greater structural parameter simply increased the sensitivity of gross-to-pay ratio to changes in the turbopump system according to equation (5). Here again the range in gross-to-pay weight ratio for the single-turbine system is small, with values varying from 23.51 to 24.08. This variation is 2.4 percent and is equivalent to 5700 pounds of gross weight with a payload of 10,000 pounds.

The differences in gross-to-pay weight ratio result from the weights of the turbopump components as well as from differences in required turbine flow. These elements in the determination of rocket gross-to-pay weight ratios are also shown in table I.

The lowest gross-to-pay weight ratio calculated for the single-turbine drive was obtained with both the axial-flow pump and the mixed-flow pump. The mixed-flow pump appears to be the better choice of these two because of the greater simplicity and lower weight. This conclusion, however, is dependent on the assumption of a constant pump efficiency of 0.7. Because significant differences in efficiency among the various pump types might change the associated gross-to-pay weight ratios, effect of efficiency must be evaluated.

Effects of Turbopump Efficiencies and Weights on Gross-to-Pay Weight Ratios

The effects of pump and turbine efficiencies on gross weight were determined by assuming three pump efficiencies, 0.5, 0.7, and 0.9, and computing gross-to-pay weight ratio for a range of bleed rates. The variation in bleed rate resulted in corresponding variations in the number of turbine stages and turbine efficiency as shown previously. This was done for one turbopump system, a mixed-flow pump driven by a single turbine, and both rocket structural weight parameters, 0.1 and 0.2. Results are shown in figure 10, which has contours of pump efficiency and turbine efficiency superimposed on the bleed-rate curves previously shown in figure 4. The ordinate and abscissa of figure 4 were selected in order to show the range in turbopump weight as well as gross weight and bleed rate. Figure 10(a) shows the variation in gross-to-pay weight ratio, turbopump weight parameter, and bleed rate for a rocket structural parameter of 0.1 and several values of pump and turbine efficiencies. The curve of $\eta_P = 0.7$ corresponds to the mixed-flow-pump - single-turbine curve shown in figure 9(a). Turbine efficiency varied from 0.5 to 0.8 for the assumed ranges of pump efficiency and bleed rate, while the ratio of gross weight to payload varied from 8.04 to 8.88 - about 10 percent. This range in gross weight occurs largely in the low range of pump and turbine efficiency, where gross-to-pay weight ratio varies rapidly with both pump and turbine efficiency. Increases in pump and turbine efficiencies above 0.7 result in relatively small decreases in gross weight, less than 3 percent.

The partial derivatives of gross-to-pay weight ratio with respect to pump and turbine efficiencies were evaluated at the point where $\eta_P = \eta_T = 0.7$, the range where the pump and turbine may be expected to operate. These derivatives indicate that 1 point in turbine efficiency is worth about 0.1 percent or 93 pounds in gross weight for a payload of 10,000 pounds, while 1 point in pump efficiency is worth 0.2 percent or 160 pounds.

Figure 10(b) shows the effects of pump and turbine efficiencies with a rocket structural weight parameter of 0.2. As before, the increase in structural parameter increased the sensitivity of gross-to-pay weight ratio to changes in the turbopump system. Gross-to-pay weight ratio varies from 22.1 to 30.8, a range of about 33 percent, with most of this variation occurring in the range of low pump and turbine efficiencies. Increases in pump and turbine efficiencies above 0.7 result in a decrease in gross weight of about 7 percent.

The partial derivatives of gross-to-pay weight ratio with respect to pump and turbine efficiency at this structural weight parameter (0.2) and efficiencies of 0.7 show that 1 point in turbine efficiency is then worth 0.4 percent in gross weight, about 890 pounds with a payload of 10,000 pounds. Similarly, 1 point in pump efficiency is worth about 0.6 percent or 1360 pounds in gross weight for a 10,000-pound payload.

The effects of turbine and pump weights on rocket gross weight were evaluated in a similar manner in order to establish the relative importance of component weight and component efficiency. This was done for the same reference point, where turbine and pump efficiencies are 0.7 in the mixed-flow-pump - single-turbine system.

Increases in turbine and pump weights resulted in increases in rocket gross weight that were less significant than those associated with changes in efficiency. With a structural weight parameter of 0.1, a 1-point increase in pump weight resulted in a gross-weight increase of 0.014 percent. Comparing this with the effect of pump efficiency shows that 1 point in pump efficiency is as significant as 13 percent in pump weight. Similarly, a 1-point increase in turbine weight resulted in a gross-weight increase of 0.017, indicating that 1 point in turbine efficiency is as significant as 7 percent in turbine weight. Calculations made with a rocket structural weight parameter of 0.2 showed approximately the same effects; 1 point in pump efficiency is as significant as 14 percent in pump weight, while 1 point in turbine efficiency is as significant as 8 percent in turbine weight.

The mixed-flow-pump - single-turbine combination was selected to evaluate the effects of component efficiency and weight because it appears to be the best system from the standpoint of simplicity, and therefore reliability, as well as gross-weight optimization. The variation in gross-to-pay weight ratio with turbine and pump efficiencies was caused by the associated changes in required bleed rate and turbine weight. The variation in gross-to-pay weight ratio with turbine and pump weights, however, was effected only by the component weights while all other parameters in the gross-to-pay weight ratio determination remained constant. Since these would be about the same for other turbopump combinations, the effect of varying turbopump efficiencies and weights with the mixed-flow-pump - single-turbine system may be considered representative of the entire group.

CONCLUSIONS

The results and conclusions of an investigation of the effects of turbopump design on gross-weight characteristics of a high-pressure bleed-type, hydrogen-propelled nuclear rocket are as follows:

1. Large numbers of turbine stages are required in order to minimize turbine flow rate and rocket gross weight. Gross weight increased significantly with all turbopump systems as the number of turbine stages was reduced below eight.

2. The twin-turbine drive system is undesirable for all of the pump types investigated. This system provided twice the exit flow area of a single turbine with the same speed and stress limits and also twice the weight for the same number of stages. The reduction in flow rate provided by the increase in exit flow area was less significant than the increase in turbine weight resulting in higher gross-to-pay weight ratios.

3. Rocket gross weight varied within 1.0 percent with twelve turbine stages in the three single-turbine systems investigated with a rocket structural weight parameter of 0.1. This range was increased to 2.4 percent with a rocket structural weight parameter of 0.2. The small range in gross-to-pay weight ratio indicates that any of the three single-turbine systems could be used with little effect on gross weight provided all pumps operated at the same efficiency, as assumed in the first part of the investigation.

4. The partial derivatives of gross-to-pay weight ratio with respect to pump efficiency indicate that 1 point in pump efficiency is worth 0.2 percent in gross weight with pump and turbine efficiencies of 0.7 and a structural weight parameter of 0.1. Increasing the structural parameter of 0.2 makes 1 point in pump efficiency worth 0.6 percent in gross weight. Similarly 1 point in turbine efficiency is worth 0.1 percent in gross weight with a structural weight parameter of 0.1, and 0.4 percent with a structural weight parameter of 0.2. The sensitivity of gross weight to turbopump efficiencies therefore depends to a great extent on the level of rocket structural weight parameter.

5. Examination of the relative importance of weight and efficiency of the turbopump components showed that 1 point in pump efficiency is as significant as 13 percent in pump weight, and 1 point in turbine efficiency is as significant as 7 percent in turbine weight in terms of the effect on rocket gross weight.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 25, 1959

APPENDIX A

SYMBOLS

A	frontal area, sq ft
g	acceleration due to gravity, 32.17 ft/sec^2
H_{SV}	suction head, ft
h	altitude, ft
$\Delta h'$	specific work, Btu/lb
I	specific impulse, sec
J	mechanical equivalent of heat, ft-lb/Btu
N	rotative speed, rpm
n	number of turbine stages
p	pressure, lb/sq in.
Δp	pump pressure rise, lb/sq in.
Q	flow rate, gal/min
r	radius, in.
$\overline{S}$	structural parameter
ΔS_{TP}	ratio of turbopump weight to propellant weight, W_{TP}/W_{pr}
SS	suction specific speed defined as $\frac{N\sqrt{Q}}{\Delta H}$
t	time, sec
U	blade speed, ft/sec
V	velocity, ft/sec
W	weight, lb
w	flow rate, lb/sec

y	bleed rate, ratio of turbine flow to pump flow
η	efficiency
λ	turbine speed-work parameter, $U^2/gJ\Delta h'$

Subscripts:

B	balance assembly
b	burnout, end of powered flight
e	empty
eff	effective
g	gross
h	hub
L	payload
P	pump
PB	pump and balance assembly
pr	propellant
T	turbine
TP	turbopump
t	tip
x	axial
1	blade row inlet
2	blade row outlet

APPENDIX B

EXAMPLE OF MATCHING PROCEDURE

The following calculation determines gross-to-pay weight ratio and number of turbine stages for a mixed-flow pump driven by a single turbine in a rocket with a structural weight parameter of 0.20 and a bleed rate of 0.025. The actual calculations were carried to more significant figures than are shown in the results in order to minimize scatter among the calculated points.

(1) $w_P N^2 = 144\times10^9$ for this pump, so $A_T/w_P = 0.00390$ according to equation (10).

(2) Figure 8(a) then shows $W_T/w_P = 0.787$ for $A_T/w_P = 0.00390$ and $y = 0.025$.

(3) $W_{PB}/w_P = 0.865$ for the mixed-flow pump and balance assembly, so $W_{TP}/w_P = 0.865 + 0.787 = 1.653$.

(4) Figure 2 shows $t_b = 336.3$ seconds for $y = 0.025$.

(5) $\Delta S_{TP} = S_{TP}/w_P t_b$ by definition, so $\Delta S_{TP} = 0.00492$.

(6) W_g/W_L from figure 4(b) is then 23.9 for $\Delta S_{TP} = 0.00492$ and $y = 0.025$.

(7) $W_T = 70\ A_T\sqrt{n}$ in equation (8), so $W_T/w_P = 70\ A_T/w_P\sqrt{n}$ and $n = 8.34$ for $W_T/w_P = 0.787$ and $A_T/w_P = 0.00390$.

This calculation is made for a range of bleed rates to obtain the curve shown in figure 9(b).

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1. Sutton, George P.: Rocket Propulsion Elements. Second Ed., John Wiley & Sons, Inc., 1956.

2. Ross, C. C., and Banerian, Gordon: Some Aspects of High-Suction Specific-Speed Pump Inducers. Trans. ASME, vol. 78, no. 8, Nov. 1956, pp. 1715-1721.

3. Lieblein, Seymour, Schwenk, Francis C., and Broderick, Robert L.: Diffusion Factor for Estimating Losses and Limiting Blade Loadings in Axial-Flow-Compressor Blade Elements. NACA RM E53D01, 1953.

4. Stewart, Warner L., Evans, David G., and Whitney, Warren J.: A Method for Determining Turbine Design Characteristics for Rocket Turbodrive Applications. NACA RM E57K25a, 1958.

TABLE I. - PUMP DESIGN PARAMETERS

[Determination for 10,000-lb payload.]

Parameters		Pump		
		Axial	Mixed flow	Centrifugal
General	H_{sv}, ft	1,150	1,150	1,150
	Δp, lb/sq in. abs	1,150	1,150	1,150
	N, rpm	20,000	20,000	16,000
	SS	19,400	19,400	15,480
	w_P, lb/sec	360	360	360
	W_P, lb	306	259	288
	W_P/w_P, lb/(lb/sec)	.850	.720	.800
	W_B/w_P, lb/(lb/sec)	.16	.14	.25
	Av. length, in.	35	36	28
	Mean diam., in.	25	32	34
Loaded stages	$r_{1,t}$, in.	5.68	4.38	3.84
	$r_{2,t}$, in.	5.68	6.28	6.64
	r_h/r_t	.6	.4	.4
	No. of blades	25	20	30
	No. of stages	8	2	2
	Rotor material	Stainless steel	Aluminum	Aluminum
	Inlet velocity, ft/sec	179	230	300
Inducer	r_t, in.	5.68	4.80	4.60
	r_h/r_t	.5	.4	.4
	No. of blades	5	5	5
	Rotor material	Stainless steel	Stainless steel	Stainless steel
	Inlet velocity, ft/sec	153	190	207

TABLE II. - WEIGHT RATIOS AND BLEED RATES FOR TURBOPUMP

SYSTEMS WITH 12 STAGES IN EACH TURBINE

Turbopump system (fig. 5)	Turbine weight parameter, W_T/w_P, $\frac{lb}{lb/sec}$	Pump weight parameter, W_P/w_P, $\frac{lb}{lb/sec}$	Balance-assembly weight parameter, W_B/w_P, $\frac{lb}{lb/sec}$	Turbopump weight parameter, W_{TP}/w_P, $\frac{lb}{lb/sec}$	Bleed rate, y	Gross-to-pay weight ratio for $\overline{S}$ = 0.1, W_g/W_L	Gross-to-pay weight ratio for $\overline{S}$ = 0.2, W_g/W_L
Single turbine:							
Axial-flow pump	0.94	0.85	-----	1.79	0.0228	8.193	23.51
Mixed-flow pump	.94	.72	0.14	1.80	.0228	8.198	23.53
Centrifugal pump	1.47	.80	.25	2.52	.0214	8.273	24.08
Twin turbine:							
Axial-flow pump	1.88	0.85	0.16	2.89	0.0207	8.322	24.43
Divided axial-flow pump	1.88	1.11	-----	2.99	.0207	8.331	24.61
Mixed-flow pump	1.88	.72	-----	2.60	.0207	8.272	24.05
Centrifugal pump	2.94	.80	-----	3.74	.0196	8.432	25.43

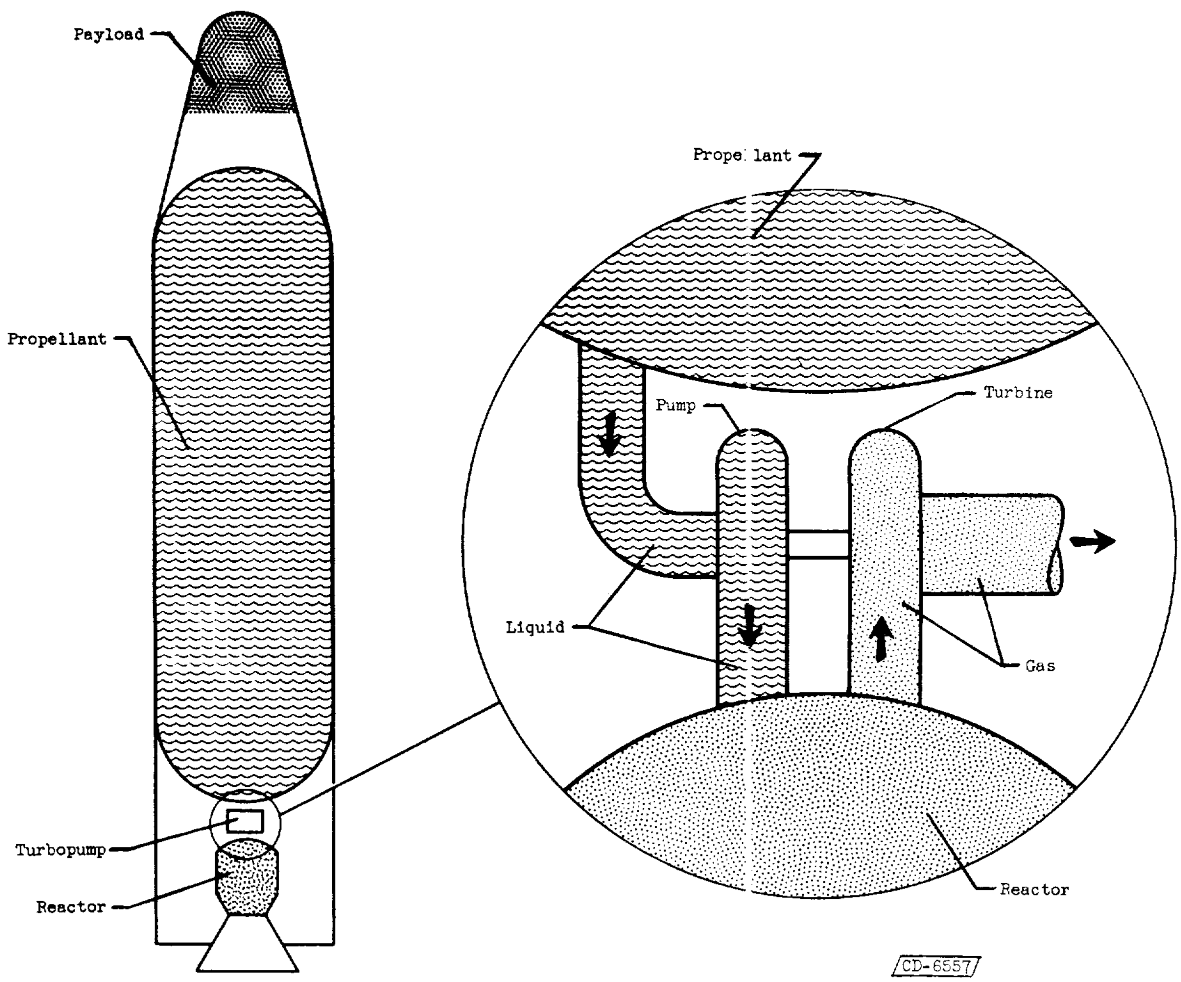


Figure 1. - Nuclear rocket with bleed system for turbopump drive.

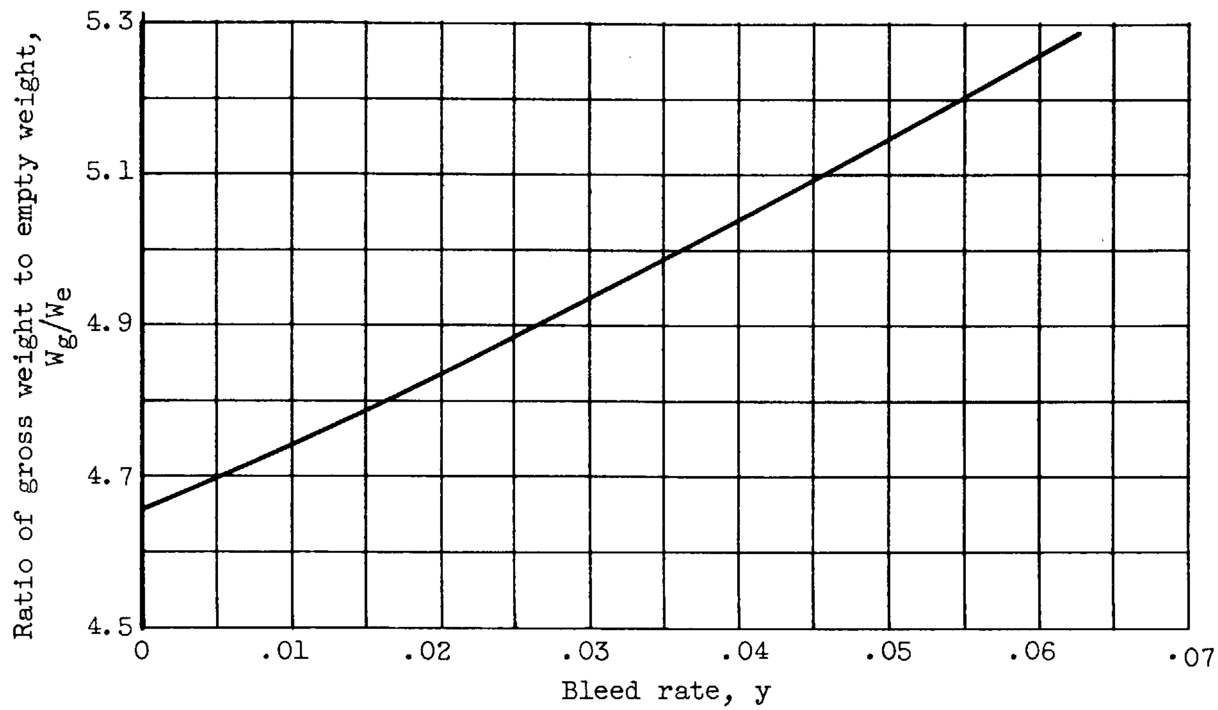


Figure 2. - Effect of bleed rate on gross-to-empty weight ratio.

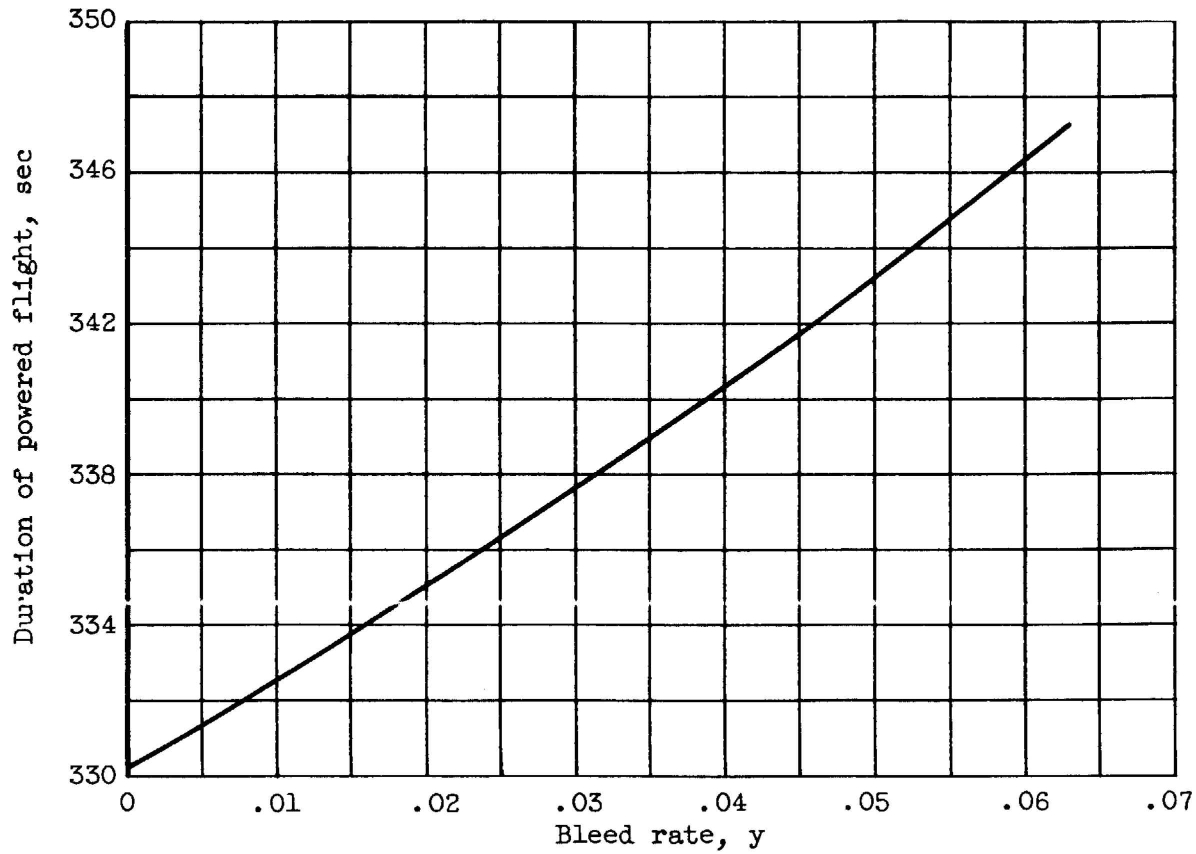
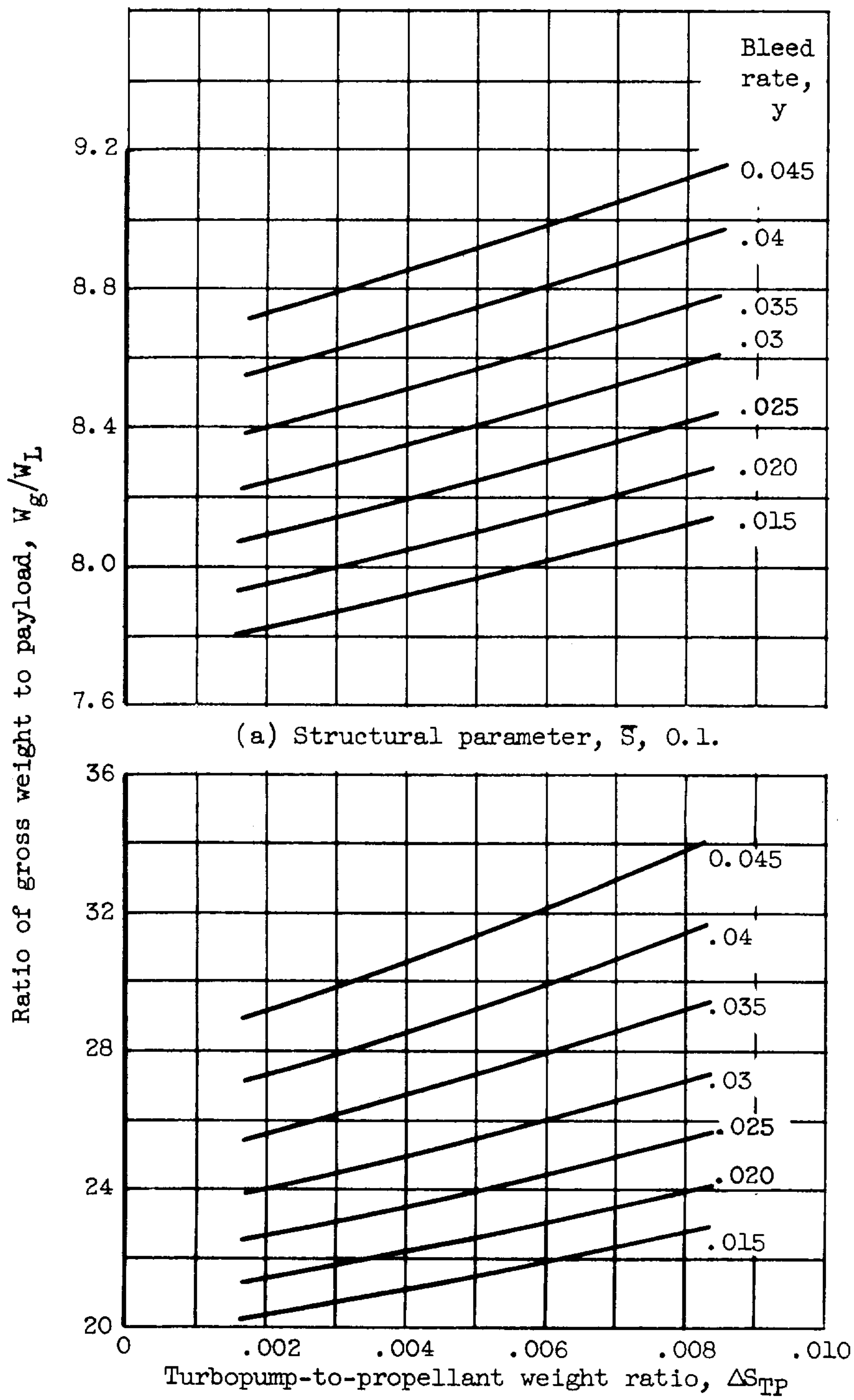
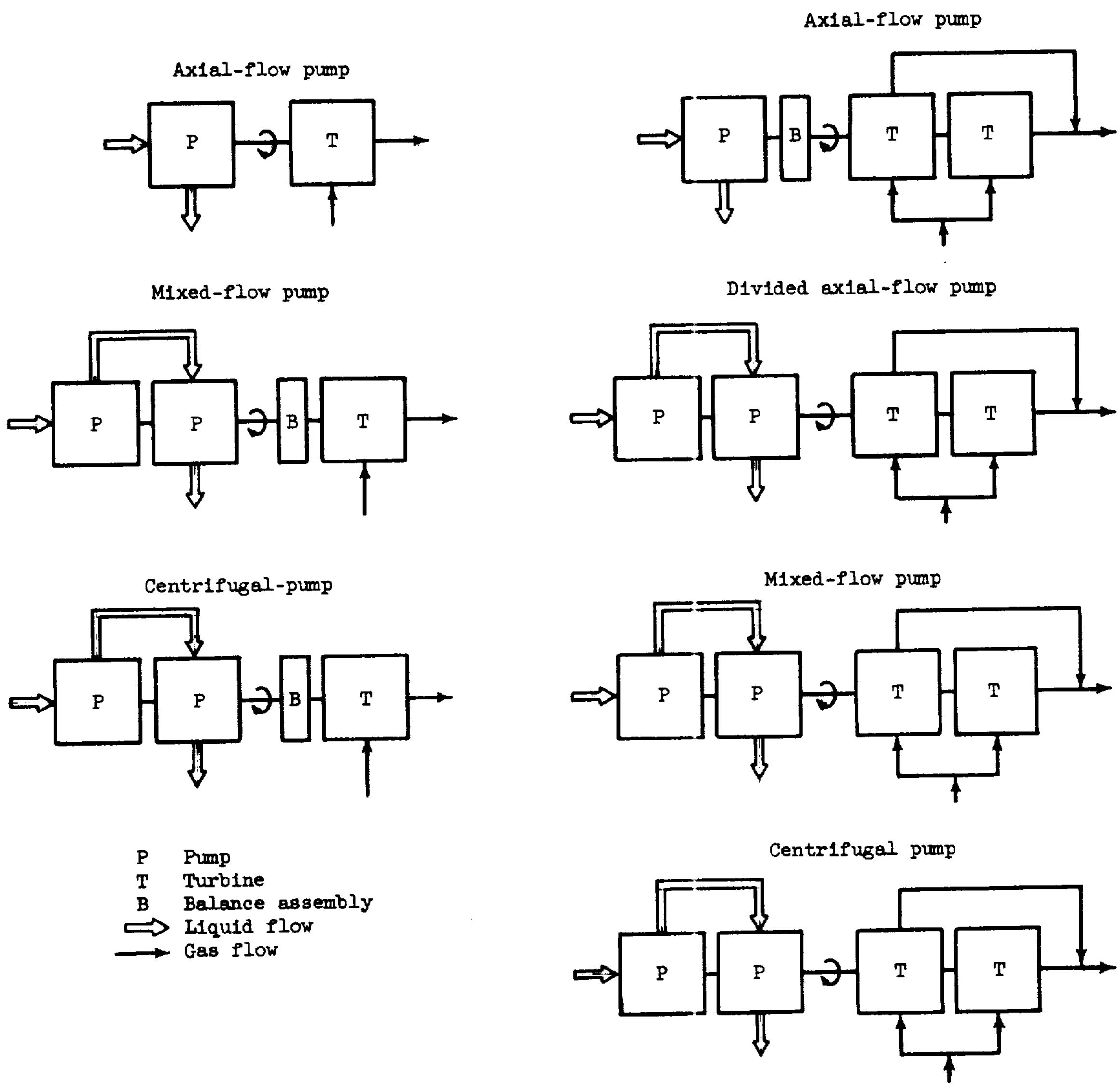


Figure 3. - Effect of bleed rate on duration of powered flight.



(b) Structural parameter, $\bar{S}$, 0.2.

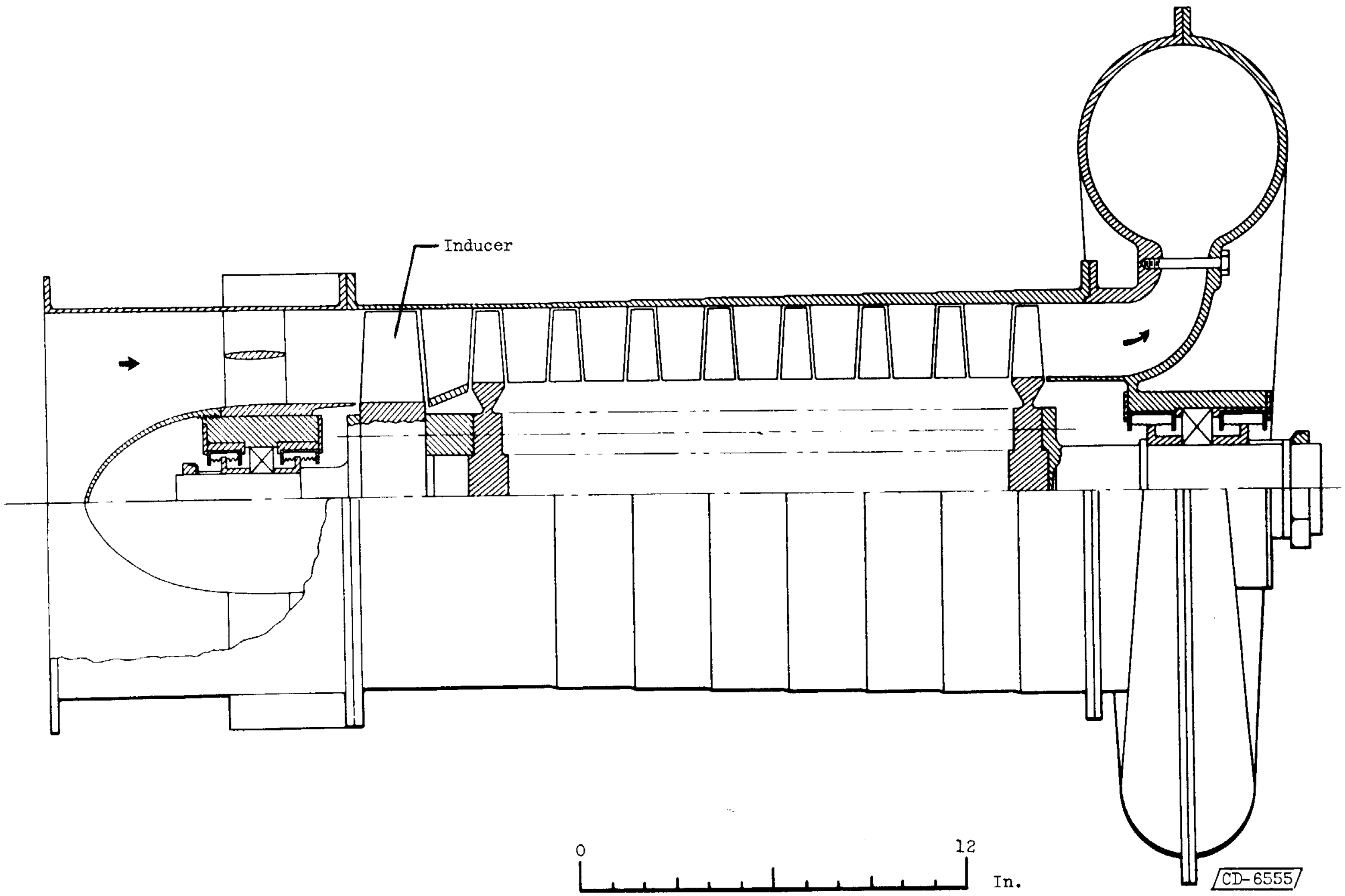
Figure 4. - Effect of turbopump weight on ratio of gross weight to payload at several bleed rates.



(a) Single-turbine drive.

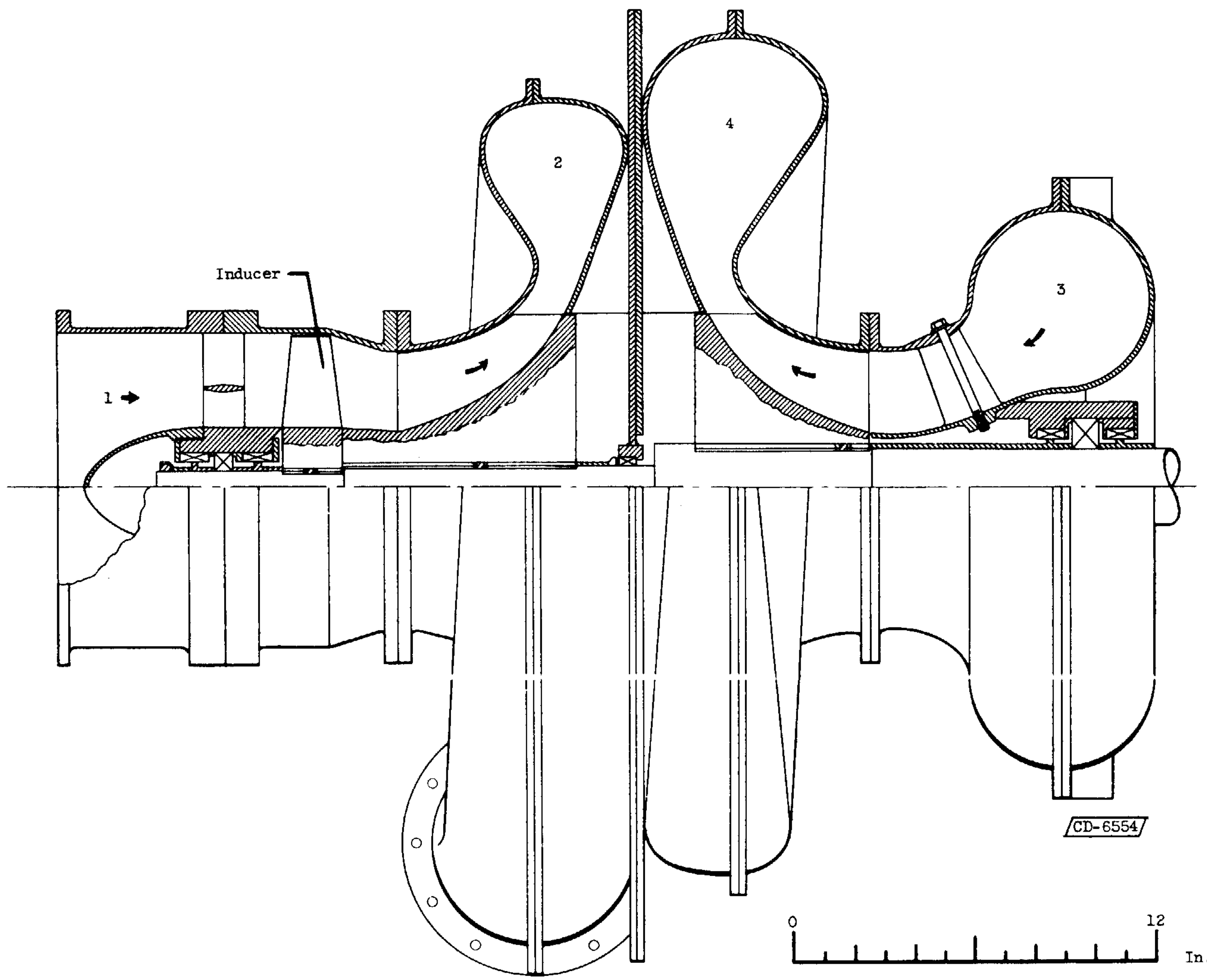
(b) Twin-turbine drive.

Figure 5. - Turbopump configurations considered for use in hydrogen-propelled nuclear rocket.



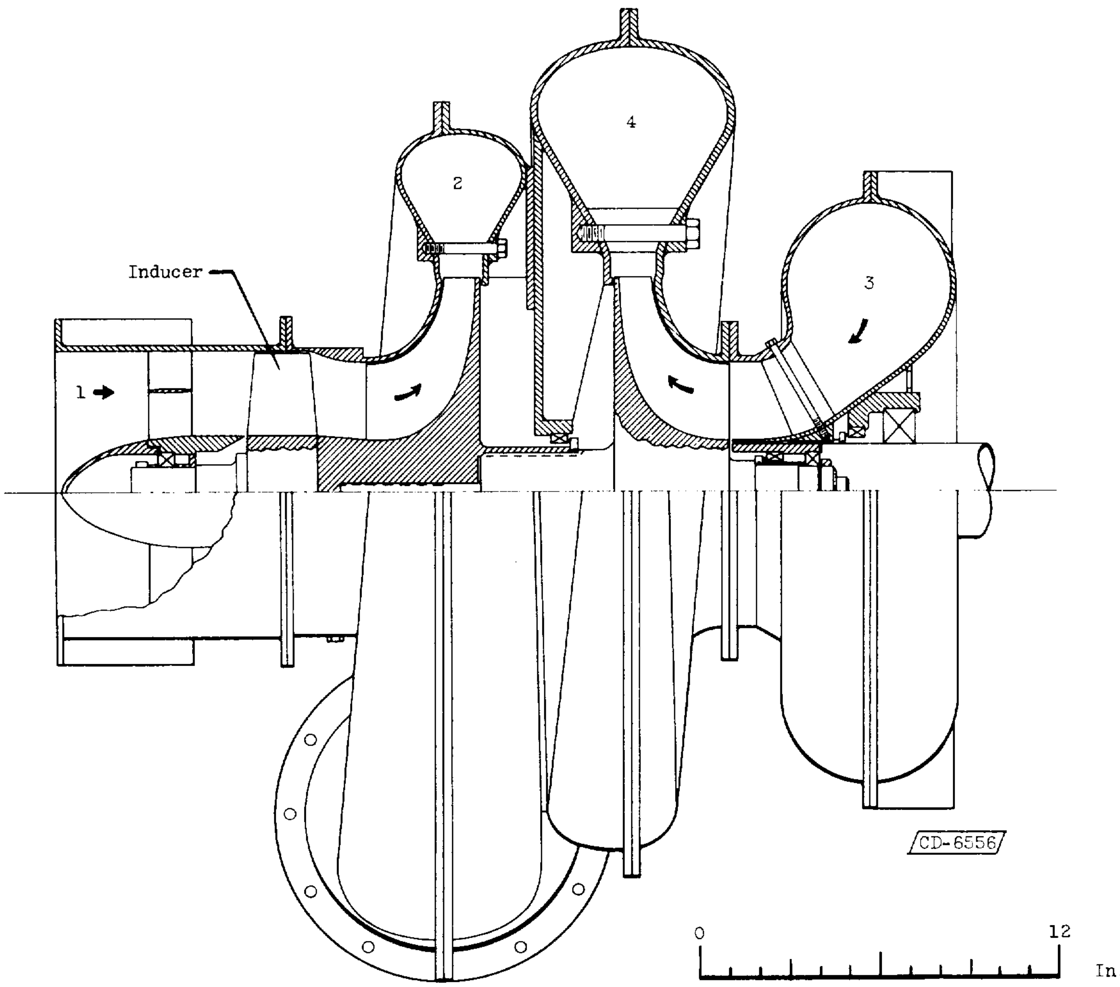
(a) Axial flow.

Figure 6. - Hydrogen pumps.



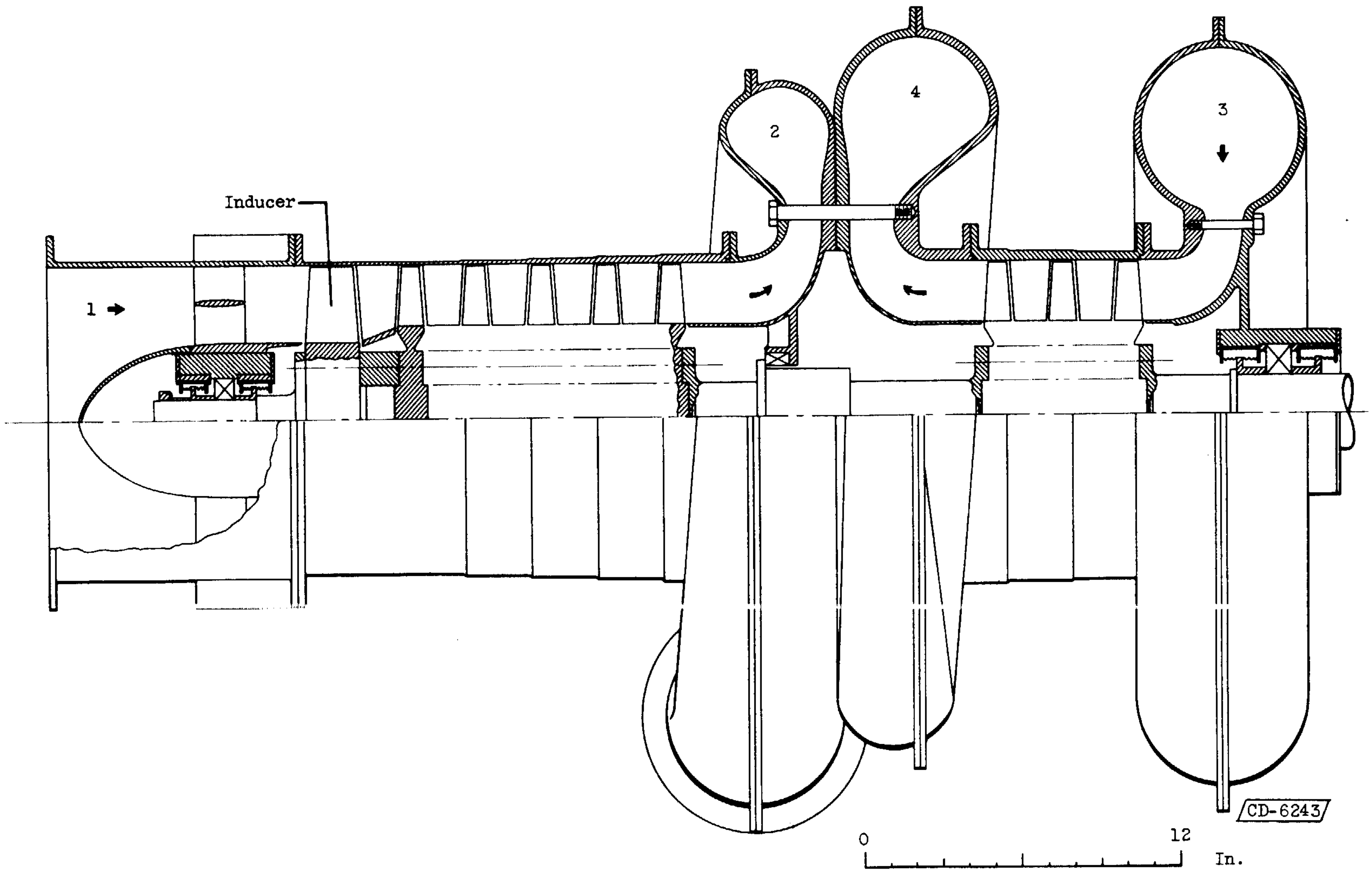
(b) Mixed flow.

Figure 6. - Continued. Hydrogen pumps.



(c) Centrifugal.

Figure 6. - Continued. Hydrogen pumps.



(d) Split axial flow.

Figure 6. - Concluded. Hydrogen pumps.

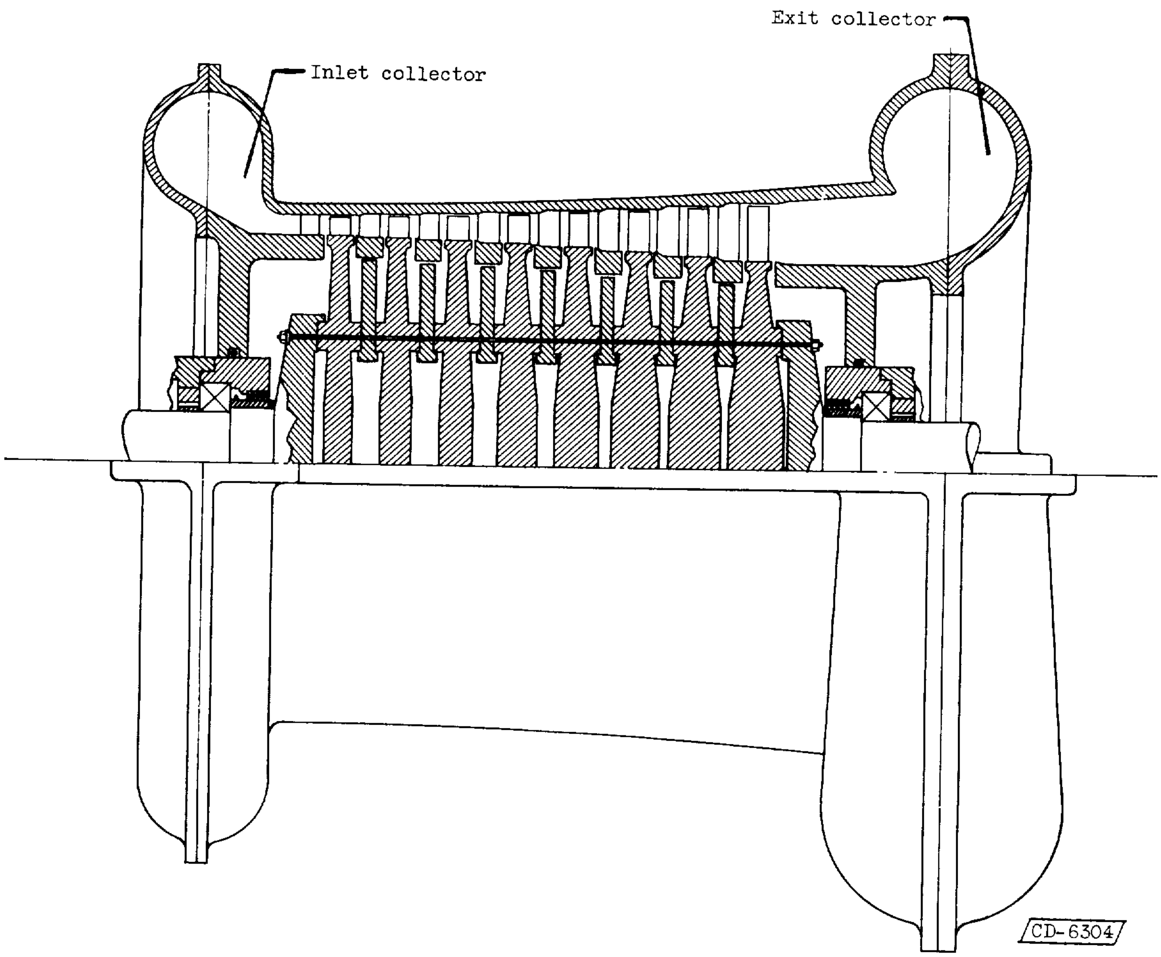
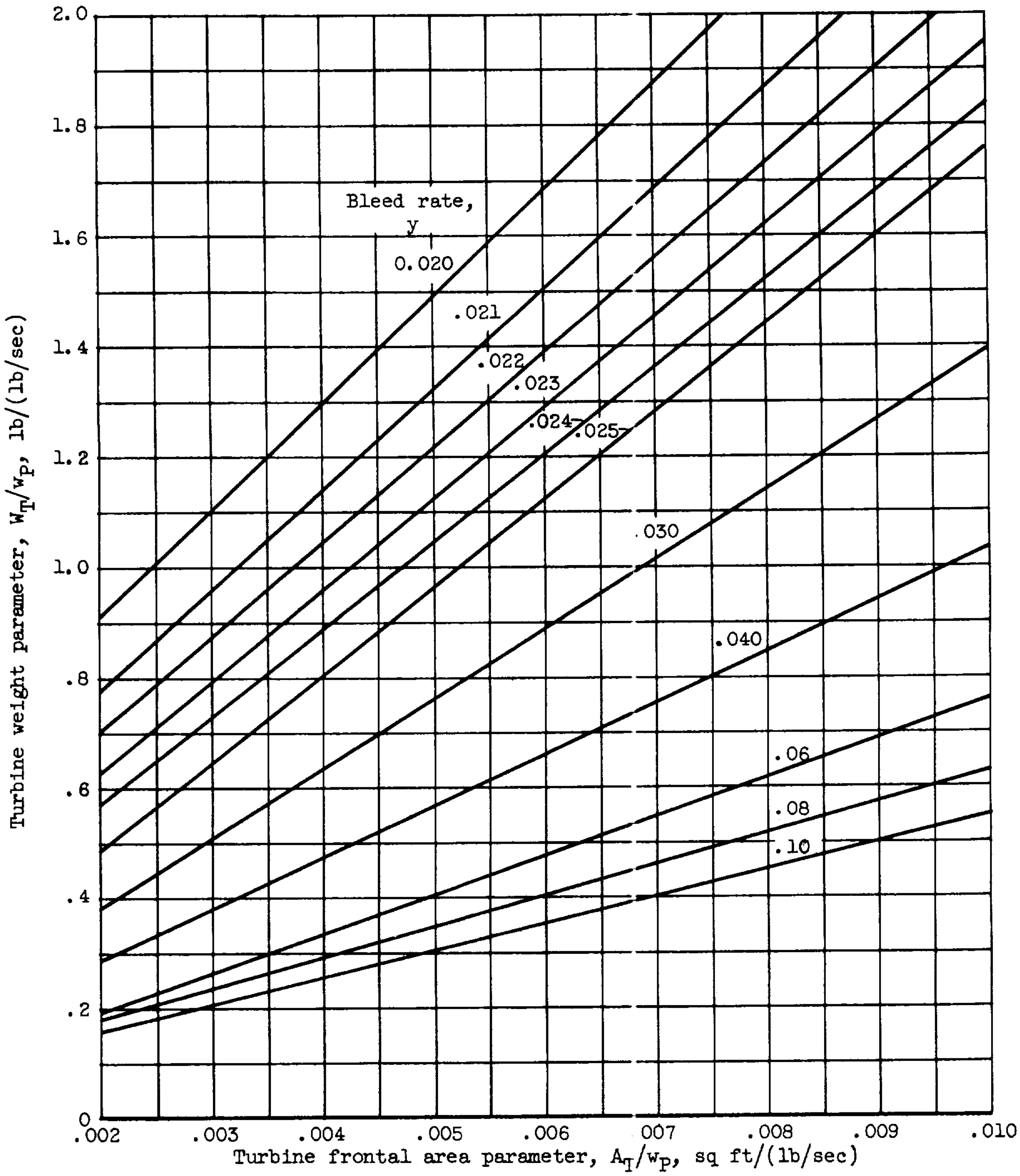
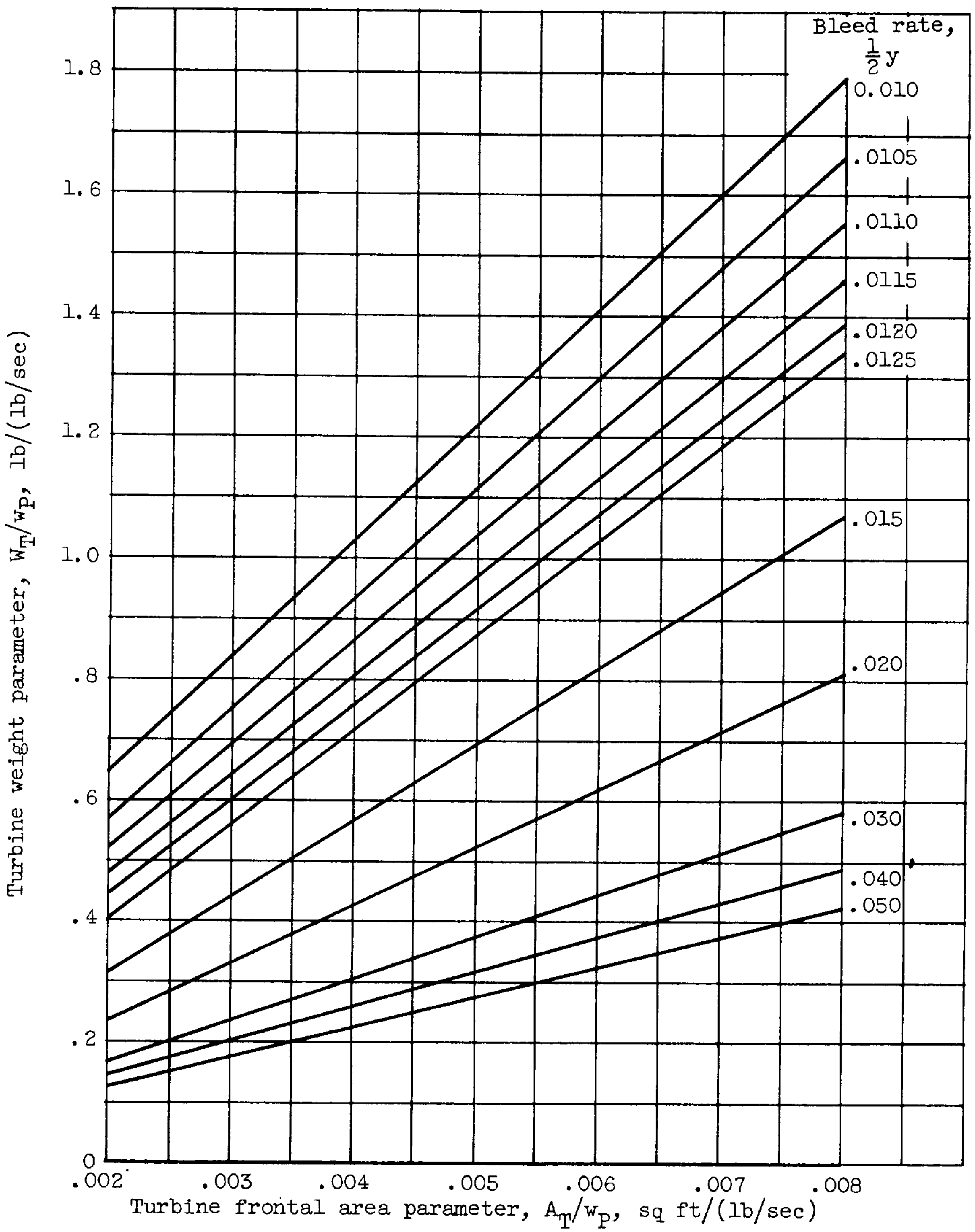


Figure 7. - Hydrogen turbine.



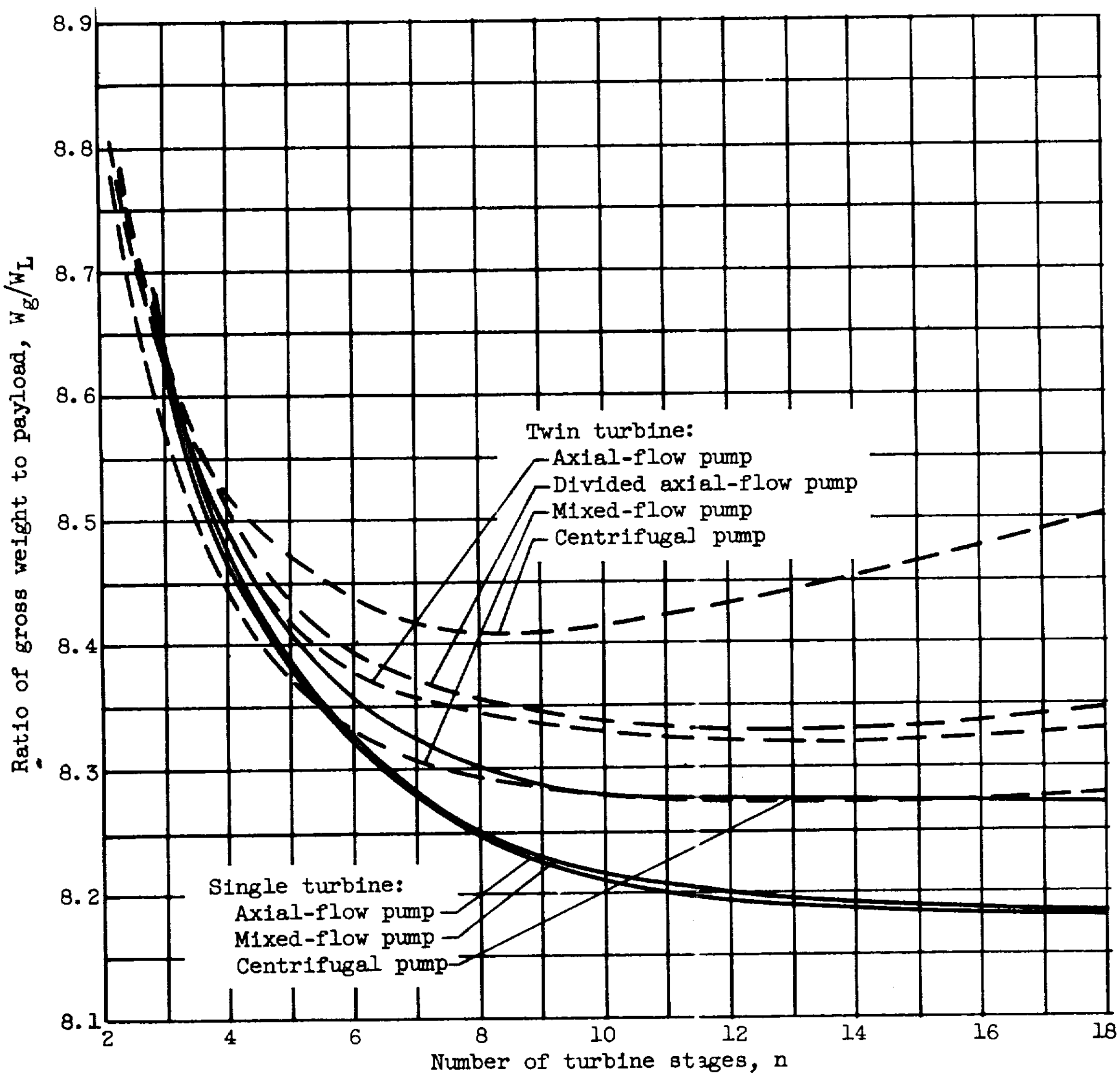
(a) Single-turbine drive.

Figure 8. - Variation in turbine weight with frontal area at several bleed rates with a pump efficiency of 0.7.



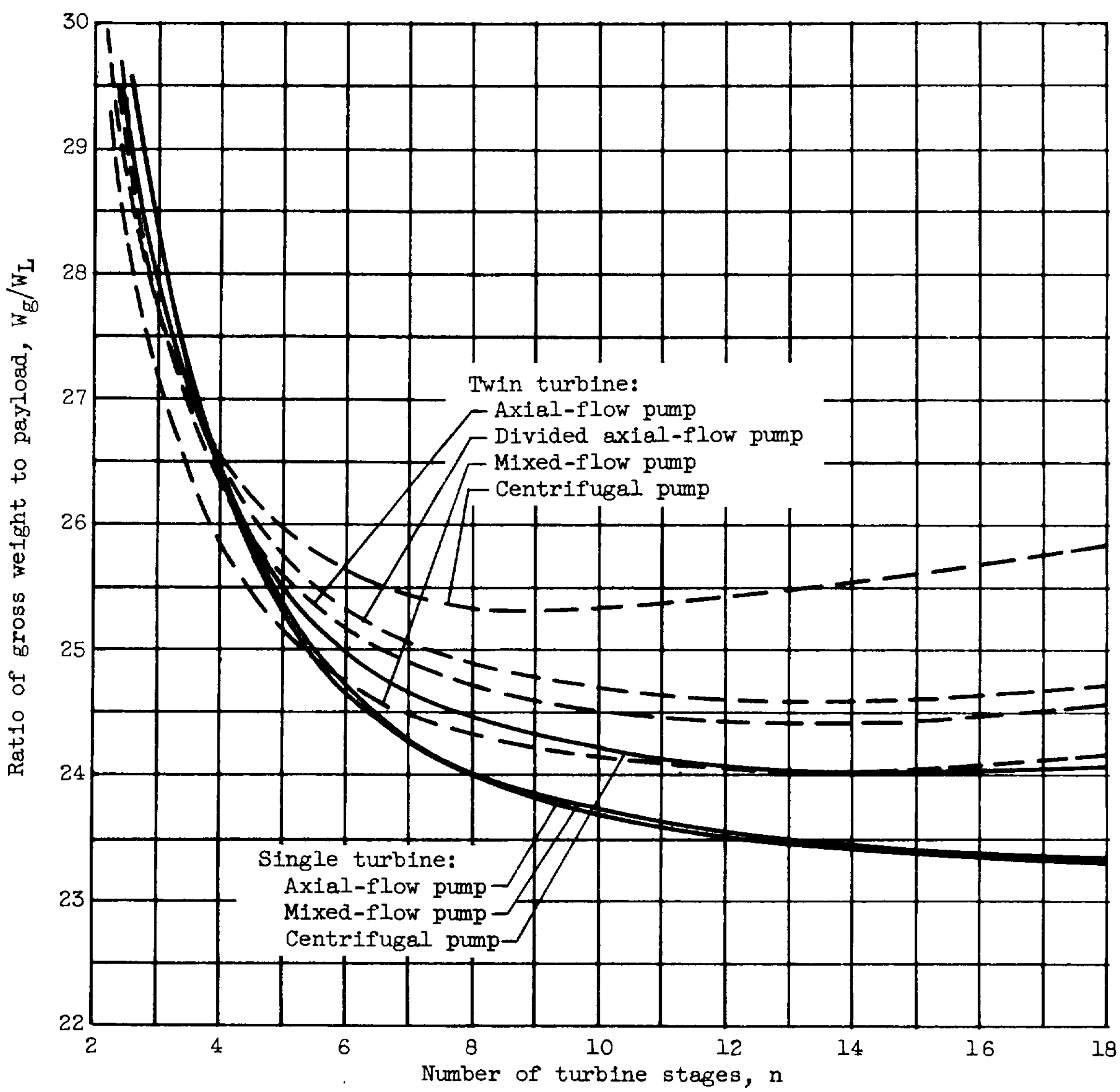
(b) Twin-turbine drive.

Figure 8. - Concluded. Variation in turbine weight with frontal area at several bleed rates with a pump efficiency of 0.7.



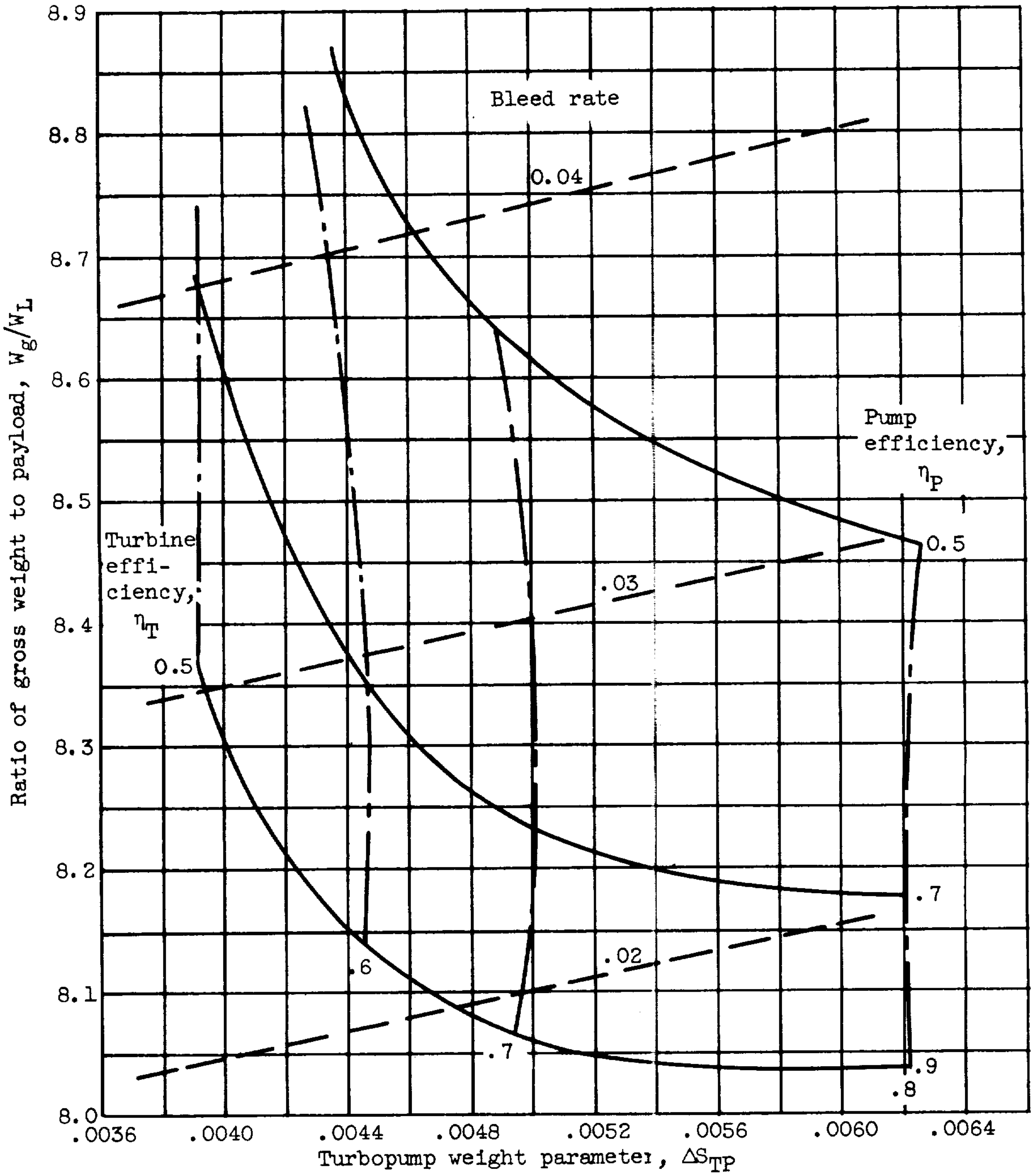
(a) Structural parameter, $\bar{S}$, 0.1.

Figure 9. - Effect of turbine-stage number on gross weight with seven turbopump systems.



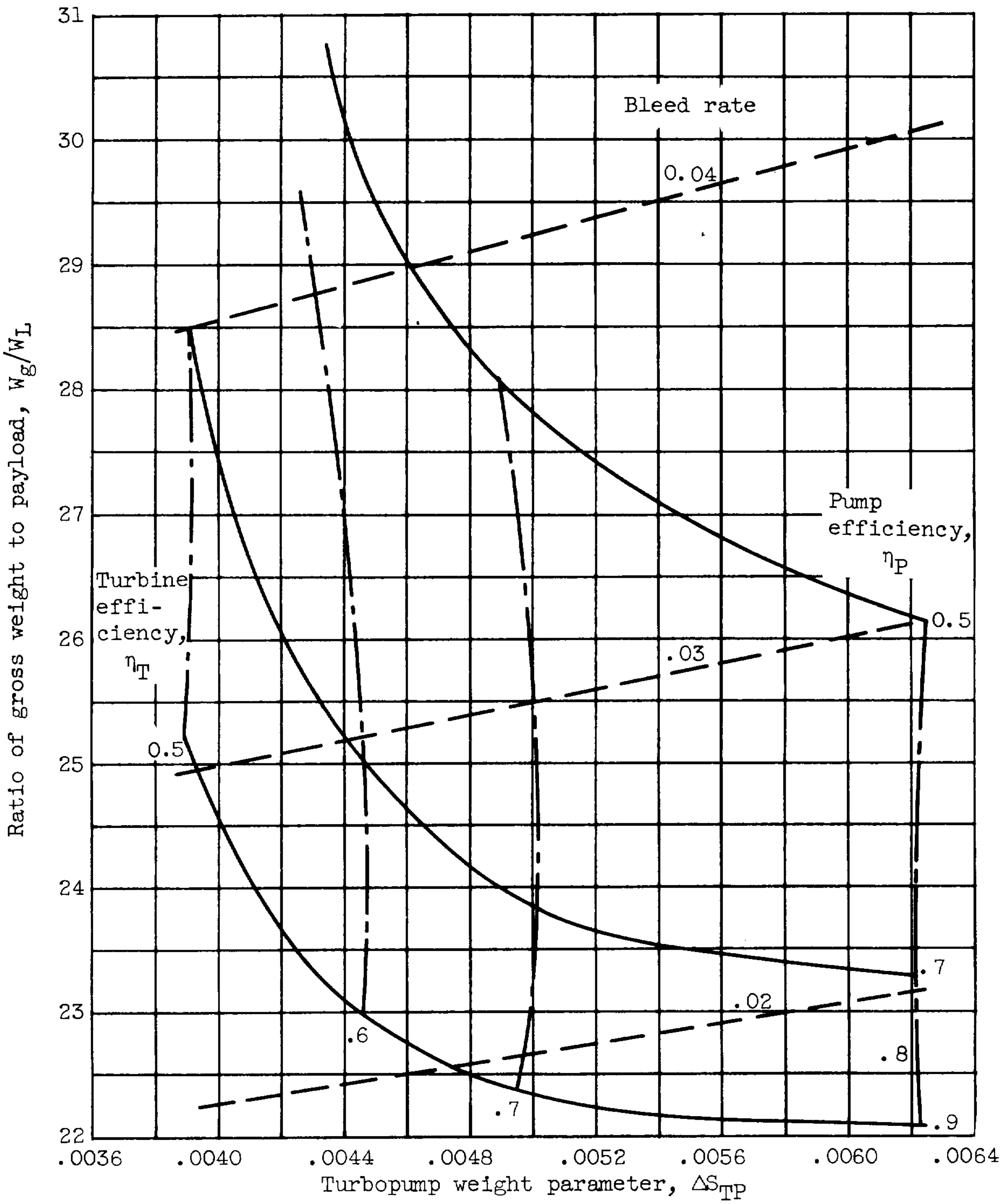
(b) Structural parameter, $\bar{S}$, 0.2.

Figure 9. - Concluded. Effect of turbine-stage number on gross weight with seven turbopump systems.



(a) Structural parameter, $\bar{S}$, 0.1.

Figure 10. - Effects of turbine and pump efficiencies on rocket gross weight and turbopump weight with mixed-flow pump and single turbine.



(b) Structural parameter, $\overline{S}$, 0.2.

Figure 10. - Concluded. Effects of turbine and pump efficiencies on rocket gross weight and turbopump weight with mixed-flow pump and single turbine.